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Wearing time and respiratory volume affect the filtration efficiency of masks against aerosols at different sizes

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ABSTRACT

Face masks are critical in preventing the spread of respiratory infections including coronavirus disease 2019 (COVID-19). Different types of masks have distinct filtration efficiencies (FEs) with differential costs and supplies. Here we reported the impact of breathing volume and wearing time on the inward and outward FEs of four different mask types (N95, surgical, single-use, and cloth masks) against various sizes of aerosols. Specifically, 1) Mask type was an important factor affecting the FEs. The FEs of N95 and surgical mask were better than those of single-use mask and cloth mask; 2) As particle size decreased, the FEs tended to reduce. The trend was significantly observed in FEs of aerosols with particle size < 1 μm; 3) After wearing N95 and surgical masks for 0, 2, 4, and 8 h, their FEs (%) maintained from 95.75 ± 0.09 to 100 ± 0 range. While a significant decrease in FEs were noticed for single-use masks worn for 8 h and cloth masks worn >2 h under deep breathing (30 L/min); 4) Both inward and outward FEs of N95 and surgical masks were similar, while the outward FEs of single-use and cloth masks were higher than their inward FEs; 5) The FEs under deep breathing was significantly lower than normal breathing with aerosol particle size <1 μm. In conclusion, our results revealed that masks have a critical role in preventing the spread of aerosol particles by filtering inhalation, and FEs significantly decreased with the increasing of respiratory volume and wearing time. Deep breathing may cause increasing humidity and hence decrease FEs by increasing the airflow pressure. With the increase of wearing time, the adsorption capacity of the filter material tends to be saturated, which may reduce FEs. Findings may be used to provide information for policies regarding the proper use of masks for general public in current and future pandemics.

1. Introduction

Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) can be spread through respiratory virus-laden droplets or aerosols that expelled by symptomatic cases or asymptomatic carriers *via* physiological activities such as coughing,

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Table 1
Description of the four types of masks used in this study.

Mask type	N95 respirator	Surgical mask	Single-use mask	Cloth mask
Size (mm)	22.0 × 16.0	18.0 × 9.5	17.5 × 9.0	20.0 × 10.5
Layers	5	3	3	3
Structure	S-M-M-M-S	S-M-S	Nonwoven cloth	Cotton fabric, 100 TPI
Manufacturer	Zhongjian Medical Equipment Co. LTD, Henan, China	Hengxin Medical Supplies Co. LTD, Qiqihar, China	Kangminweicai Co. LTD, Xinxiang, China	Home-made

Abbreviation: S: Spunbond; M: Meltblown.

sneezing, talking, singing, and breathing (Bahl et al., 2020; Liu et al., 2020b; Tang et al., 2020). Larger droplets usually settle quickly within a short distance from the source, while smaller aerosols could suspend in the air for hours and travel longer distances, leading to airborne transmission. With the exponentially increasing number of coronavirus disease 2019 (COVID-19) cases worldwide, there is an urgent demand for simple and effective protective and control measures at both the individual and community levels, even while vaccines are rolled out.

Wearing face masks, as a basic non-drug and low-cost intervention, can curb the transmission of SARS-CoV-2 and significantly reduce the risk of COVID-19 infection (Chu et al., 2020). The World Health Organization (WHO) recommends the use of masks in potentially high transmission places and public places where other preventive measures (e.g., physical distancing and vaccination) are not possible during COVID-19 pandemic (WHO, 2020). Many countries including China, the US, and UK have mandated masks in public places. The global demand for masks has thus increased sharply, and the number of daily mask use in Asia alone exceeds 2.2 billion (Sangkham, 2020). Different types of masks have distinct FEs with differential costs and supplies. Personnel are thus recommended to wear different types of masks under distinct scenarios of COVID-19 infection risks to ensure the protection effect, avoid unnecessary mask cost, and reduce environmental pollution due to incorrect dispose of used masks.

There are many factors that significantly affect the effectiveness of masks, including amount of respiratory activity in a given space, droplet/aerosol particle size, mask type, breathing volume, wearing time, leakage rate, and mask humidity (van der Sande et al., 2008; Chia et al., 2020; Milton et al., 2013). The tightness of the mask is a very important factor (Grinshpun et al., 2009; Steinle et al., 2018), which is related to the type, size, and material selection of the mask, as well as the age, gender, and even race of the person wearing the mask. Small gaps between the mask material and skin can lead to substantial decreases in the overall filtration efficiency. As an example, for aerosols <2.5 mm, filtration efficiency could decrease by 50% for a relative leak area of 1% (Drewnick et al., 2021). In order to avoid this from interfering with the evaluation of mask efficiency, we used tape to seal the edges of the mask. Although the continuous or intermittent use time of 8 h of N95 mask is recommended by the National Institute for Occupational Safety and Health (NIOSH), the US Centers for Disease Control and Prevention (US CDC) (Planning, 2020), and the China Medical Protective Mask Standards, there is a lack of research on the impact of wearing time (e.g., from 0 to 8 h) (MoH, 2009) under different physiological conditions (e.g., singing, speaking, and breathing), with different breathing volumes (Gregson et al., 2020). According to previous literature, healthy adults breathe approximately 8, 22, and 33 L/min during light, moderate, and heavy physical activities, respectively (Ping et al., 2014), and different particle sizes and concentrations of inhalable aerosols are then produced. However, few studies have focused on the effectiveness of different mask types to a broad range of aerosol particle size at different breathing depths with different duration of wearing.

The aim of this study was (1) to evaluate the inward and outward FEs of four masks types (N95 respirator, surgical mask, single-use mask, and cloth mask) typically used during this epidemic, and (2) to access the impact of several key factors [different breathing volumes (15 and 30 L/min) and wearing times (0, 2, 4, and 8 h)] on their filtration performance against different sizes (0.3∼10 μm) of aerosol particles. The findings may enhance the scientifically basis of self-protection for the general public during the current and future pandemics.

2. Materials and methods

2.1. Masks

We did not attempt to assess all commercially available face masks but only focused on major categories that are most representative and common use of general public during this pandemic. Three different types of commercially available masks plus a common home-made cloth mask were thus tested (Table 1 and Fig. 1A).

2.2. Measurements

All tests were carried out in a mixing chamber (1.5 m × 1.0 m × 1.2 m) with HEPA to ensure the cleanliness of the initial air. The relative humidity (RH) and temperature of the test chamber were maintained at 40–45% and 21–23 °C, respectively. Simulated body fluid (SBF) was used in the test according to a previous study (Oyane et al., 2003). The polydispersed salt composition of the SBF is similar to the composition of the aerosol breathed by human, non-toxic and

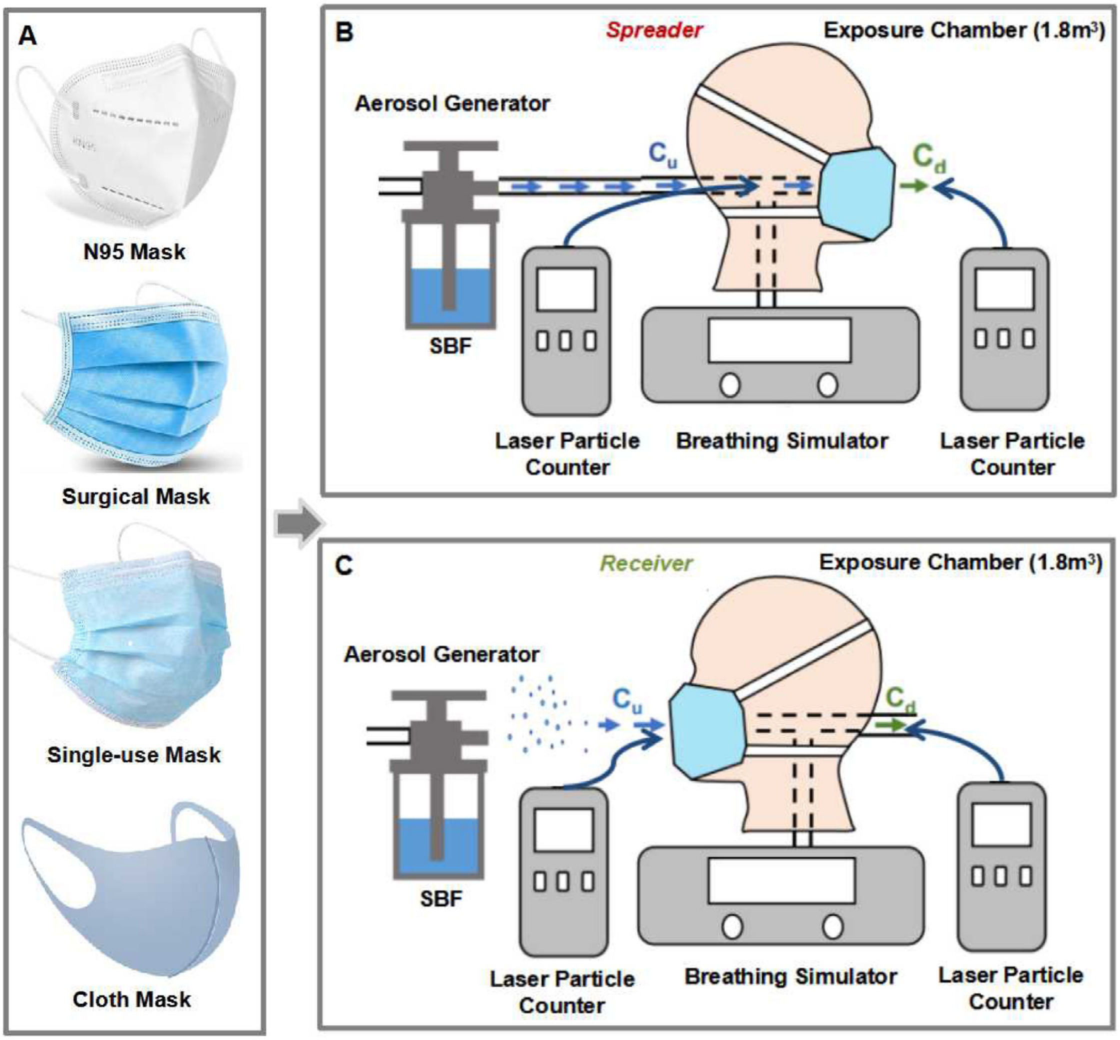

Fig. 1. Schematic of the experimental setup for four different mask types (A) in a mixing chamber. A mist of simulated body fluids (SBF) was produced by an aerosol generator and introduced into or ejected from the mouth of a standard mannequin head to imitate a receiver (B) and a spreader (C). An artificial breathing simulator was set in a lung ventilation rate to be representative of a steady state of an adult breathing. Gaps between the mask and face counter were completely sealed by medical tapes. The particle size of droplets/aerosols as well as upstream (C_u) and downstream (C_d) concentrations were measured by two laser particle counters.

thus can be used for aerosol simulation test. SBF aerosols with particles size ranging from 10 nm to 10 μm were generated by an aerosol generator (6-Jet, BGI CN31 Collison, USA). Laser Particle Counters (Y09-301, AC-DC, Jiangsu Sujing Group Co., Ltd., China) were used to measure particle sizes and concentrations of the aerosols (The range were 0.3–10 μm).

For outward measurements (Fig. 1B), aerosols were introduced into an oral cavity of a standard mannequin head to test the outward FEs of masks. The standard mannequin head connected to an artificial breathing simulator was representative of a steady state of respiratory volumes of adults with four different types of masks. The gaps around the mask and face contour were completely sealed with medical adhesive tape on the standard mannequin head to prevent leakage to test the FEs of the masks under ideal conditions without leakage. For inward measurements (Fig. 1C), the aerosols were introduced into a mixing chamber along with inlet air and then well mixed in the chamber with the aid of a micro fan before the FE test.

Two laser particle counters were used to measure particle sizes and concentrations of the upstream (C_u) and downstream (C_d) aerosols flowing through masks, respectively. Aerosols were measured for a total duration of 1 min and approximately 2 cm away from the mannequin head. Real-time particle number concentrations with a size ranging at 0.3, 0.5, 1, 3, 5, and 10 μm were obtained.

Considering the recommended wearing time of N95 respirator by WHO and of the surgical mask by Chinese medical standards, a maximum wearing time of 8 h was chosen for this study. We recruited volunteers (4 men and 4 women) with verbal consent to wear four types of masks. Each of which was worn for 2, 4, and 8 h, and then immediately collected and tested. A brand-new mask that has never been worn was used as the 0 h sample.

The breath rates of adults are approximately 8, 22, and 33 L/min during light, moderate, and heavy activities, respectively (Ping et al., 2014). The FEs of masks were thus compared at two different breathing volumes of 15 L/min (tidal volume of 0.5 L/breath, respiratory rate of 30 breaths/min) and 30 L/min (tidal volume of 1.0 L/breath, respiratory rate of 30 breaths/min), which were controlled by flow valves and a mass flow meter (LZB-10WB, Changzhou Qinfeng Co., Ltd., China) across multiple mask usage times (0, 2, 4, and 8 h). For each combination of mask type, breathing volume, and wearing time, both inward and outward measurements were repeated 8 times ($n = 8$). The chamber was flushed out with clean air by HEPA after each test to avoid cross-contamination of SBF aerosols.

2.3. FEs

The mask FEs were calculated using the following formula:

$$\text{FEs} = \frac{C_u - C_d}{C_u} \times 100\%$$

The aerosol was sampled before (upstream, C_u) and after (downstream, C_d) passing through the mask.

2.4. Statistical analysis

Statistically significant differences were evaluated by the Fisher's least significant difference (LSD) test and Analysis of Variance analysis (ANOVA) with Bonferroni correction in R version 4.0.1 using '*agricolae*' and '*ggpubr*' packages. Statistical significance was considered when $p < 0.05$, and confidence interval (CI) was 95% throughout. The differences between four mask types, particle size, respiratory volume, and usage time at inward and outward groups were compared by ANOVA. Multiple comparisons among four different mask types were developed by LSD test.

3. Results and discussion

In the present study, an SBF system was used to evaluate the protective effect of masks against aerosols. In the case of two different breathing volumes (15 and 30 L/min), we determined the inward and outward FEs of four types of masks (N95, surgical, single-use, and cloth masks) on various aerosol particle sizes between 0.3 and 10 μm. The inward and outward filtration effects of masks with different wearing times (0, 2, 4, and 8 h) were also compared. Due to the noise in the measurement, some FE values are lower than 0, which is unrealistic. Therefore, negative FE values are no longer considered in graphs, tables, and further calculations, the rest valid values are reported in Fig. 2 and **Table S1**.

3.1. Mask type was a main factor affecting FEs

Outward and inward FEs of four different mask types were presented in **Table S1** and Fig. 2. The inward and outward FEs of brand-new N95 [FE(%) $\geqq 99.46 \pm 0.01$] and surgical mask [FE(%) $\geqq 97.38 \pm 0.07$] against different particle sizes remained the same under two different respiratory volumes. This is in line with a meta-analysis of randomized controlled trials showing that, among health care providers, N95 respirators and surgical masks were equally effective in preventing influenza diseases (Long et al., 2020). However, some meta-analyses show N95 were superior (Chu et al., 2020), and the fit was the key difference since a surgical mask allows unfiltered air through the gaps. The FEs of single-use polypropylene (nonwoven cloth) masks and self-made cloth masks were significantly decreased compared to N95 and surgical masks. As an example, the average FEs (%) of single-use masks for a particle size of 0.3 μm were 68.05 ± 0.73 (outward) and 51.55 ± 0.59 (inward), respectively, and the average FEs (%) of cloth masks against particle size of 0.3 μm were 35.91 ± 0.27 (outward) and 24.74 ± 0.13 (inward), respectively.

The FEs of cloth masks is closely related to the material type, number of layers of fabric, and yarn count (Zhao et al., 2020). Previous study showed that all fabric masks tested were at least 50% efficient (Whiley et al., 2020), but the FE (%) of the 2-layer quilt (80 TPI) and 2-layer cotton (600 TPI) against particles <300 nm was 38 ± 11 and 82 ± 19, respectively. Our study shows the FEs(%) of the self-made cloth masks (100 TPI) was $\geqq 35.91 \pm 0.27$. Therefore, compared with N95 and surgical masks, 3-layer cotton masks may not be able to completely block the transmission of SARS-CoV-2 aerosols, for which size distributed in sub-micron (0.25–1.0 μm) and ultra-micron ranges (1–4 μm and > 4 μm) with low fabric threads number (Liu et al., 2020b; Chia et al., 2020). For health care workers (HCWs) who are at high risk of opportunistic airborne transmission, the use of N95 respirators or surgical masks is sufficient to filter against aerosols containing SARS-CoV-2. People of low-risk area could choose lower cost single-use masks or cloth masks with rational fabric in case of the shortages of surgical face masks or N95 respirators.

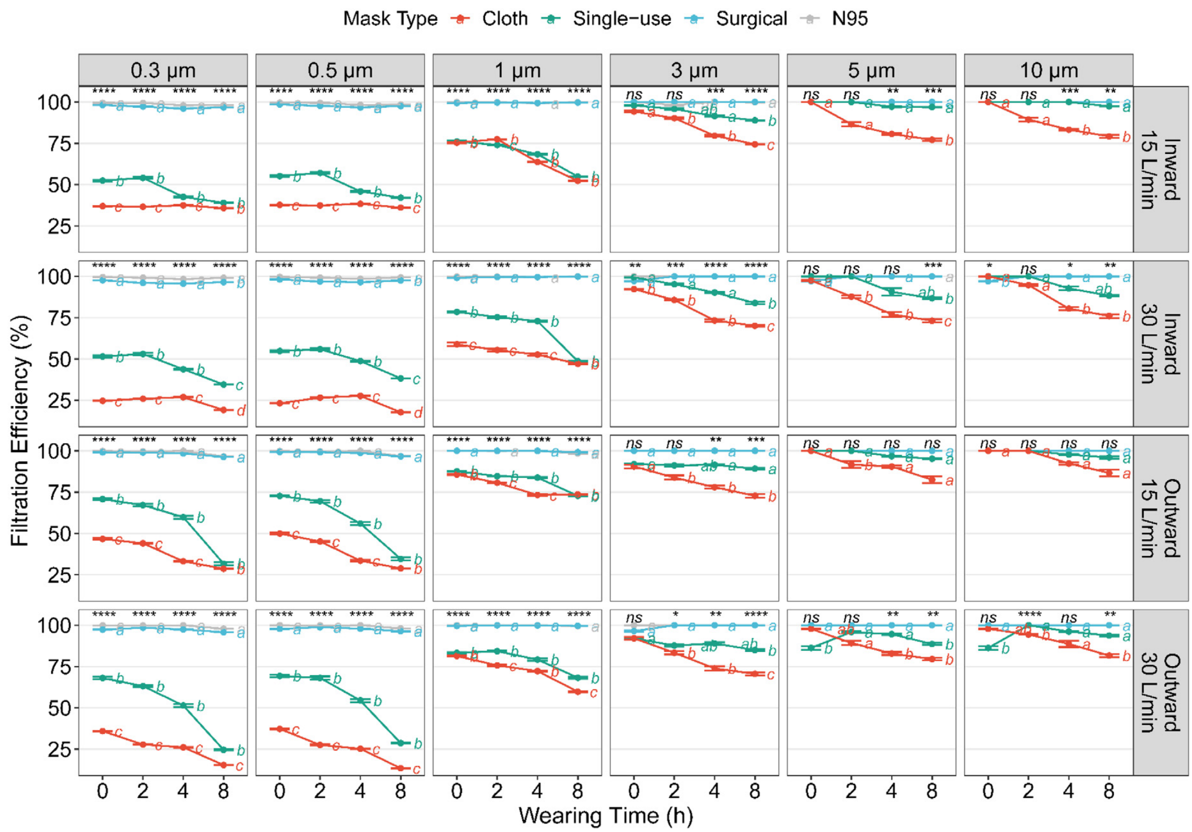

Fig. 2. Plot shows the outward and inward FEs(%) of four different types of masks wearing for 0, 2, 4, and 8 h against different sizes (0.3∼10 μm) of droplets/aerosols generated under two different breathing volumes (15 and 30 L/min). Each mask type was measured for eight times (n =8). Statistically significant differences among four mask types are given by using ANOVA with Bonferroni correction. The letters of alphabet (a, ab, b, and c) indicate statistically significant differences of FEs among four masks by applying LSD test (*$p \leq 0.05$, **$p < 0.01$, ***$p < 0.001$, and ****$p < 0.0001$).

3.2. Masks exhibited different FEs for aerosols at different sizes

The FEs of masks decreased significantly with decreasing aerosol particle size. The FEs of all four types of masks were all >90% for aerosols particle sizes > 3μm with no statistically significant difference (**Figure S1**). It was consistent with the previous research showing that surgical masks greatly reduce the exhaled "fine" aerosols (≤5 μm) and "coarse" droplets (> 5μm) from volunteers suffering from influenza, and the reduction in the "coarse" droplets part is greater (Lindsley et al., 2014; Migliori et al., 2019). Among four types of masks, we found that the difference in FEs of aerosols with a particle size < 1 μm was significant. More specifically, the FEs of N95 [FE(%) ≧ 99.46 ± 0.01] and surgical masks [FE(%) ≧ 98.16 ± 0.02] were significantly higher than those of single-use [FE(%) ≧ 52.41 ± 0.54] and cloth masks [FE(%) ≧ 36.99 ± 0.16]. Our findings that cloth masks had the lowest efficiency for both sub-micron and super-micron size particles are consistent with previous results (Liu et al., 2020a). As the particle size increases, the FEs of four types of masks tend to increase, indicating that their FEs for coarse aerosols are better than that for fine aerosols. The main filter material of the mask is polypropylene melt blown cloth, and the filtration mechanism mainly includes diffusion deposition, interception deposition, inertial deposition, and electrostatic attraction deposition. The smaller the particle, the stronger the effect of diffusion deposition and electrostatic attraction deposition. The larger the particle, the better the effect of trapped deposition and inertial deposition.

Mounting evidences demonstrate that SARS-CoV-2 spreads through both large droplets and small aerosols (Fennelly, 2020; Stadnytskyi et al., 2020), and the smaller viral-laden aerosols have been shown to be suspended in the air for 16 h (Huang et al., 2020). Although the detailed transmission of SARS-CoV-2 are not yet fully understood, droplets/aerosols < 5μm are considered to be the main source of transmission of respiratory infections (van der Sande et al., 2008; Wang et al., 2020). Surgical masks have been found to efficiently reduce SARS-CoV-2 virus in respiratory droplets/aerosols, especially for particles < 5μm (Leung et al., 2020). Therefore, in relatively high infection risk locations, wearing N95 or surgical masks is required in order to provide full particle size protection.

3.3. FEs significantly decreased with increasing duration of wear

Some previous studies have shown that medical personnel wearing N95 masks for several hours can provide safe protection (MoH, 2009; Radonovich et al., 2009; Rebmann et al., 2013). In the present study, when wearing N95 and surgical masks for 0, 2, 4, and 8 h, their inward and outward FEs (%) ranged from 96.61 ± 0.09∼100 ± 0 and 95.75 ± 0.09∼100 ± 0, respectively. Our results indicated that N95 and surgical masks could provide stable protection efficiency within 8 h usage, supporting the 8 h continuous or intermittent usage time recommended by NIOSH and US CDC (Planning, 2020). As proposed in China Medical Protective Mask Standards, the effectiveness of surgical masks is continuously applied for 6–8 h and should be replaced in time if they are polluted or wet.

The FEs results of single-use and cloth masks under two breathing volumes of 15 and 30 L/min were given in **Figure S2**. FEs of single-use masks wearing for 2 and 4 h showed no statistically significant difference compared to 0 h. However, there was a significant difference at 8 h, suggesting that the optimal wearing time of single-use masks may somewhere between 4 and 8 h. The FEs of cloth masks significantly reduced after 2 h under deep breathing (30 L/min), suggesting that the guaranteed effective wearing time may be <2 h. To date, in terms of product standards, there is no stipulation regarding how long face masks should be used, and commercial masks are rarely marked with the recommended time for usage. For the general public, it is recommended to guide the general public for proper use and reuse face masks to avoid overuse, overprotection, and white pollution.

3.4. Mask had differential inward and outward FEs

The inward and outward FEs results of four different masks were showed in **Figures S3**. When the aerosol particle size was < 1μm, the outward FE(%) [71.1 ± 31.39 (0.3 μm), 72 ± 31.1 (0.5 μm), and 88.8 ± 13.5 (1 μm)] was significantly greater than inward FE(%) [68.1 ± 31.1 (0.3 μm), 69.2 ± 30.7 (0.5 μm), and 82.1 ± 20.6 (1 μm)]. For particle size 10 μm, the statistically significance is not as obvious as particle size < 1 μm. However, for particle size between 3 and 5 μm, there is no statistically significant difference. This result is contrary to the previous findings showing that the inward protections of self-made cloth mask, surgical mask, and N95 was more effective than their outward protection (van der Sande et al., 2008). However, this previous study did not compare the FEs of masks for aerosols at different particle sizes.

3.5. FE decreased with the increasing respiratory volume

The FEs of four masks at two differential respiratory volumes of 15 and 30 L/min were significantly affected by aerosol particle size (**Figure S4**). When the aerosol particle size was < 1μm, the FEs (%) of deep breathing [67.5 ± 33.2 (0.3 μm), 68.6 ± 33.1 (0.5 μm), and 84 ± 19.8 (1 μm)] were significantly lower than those of normal breathing [71.7 ± 28.9 (0.3 μm), 72.5 ± 28.5 (0.5 μm), and 86.8 ± 15.4 (1 μm)]. However, there was no statistically significant difference for particle sizes ranging between 3 and 10 μm. This is different from the findings of van der Sande et al. (2008) showing that the protection effect of masks was not affected by physical intensity activity (e.g., the depth of breathing). It should be noted that the artificial respiration simulator is different from real human breathing, and the exhalation and inhalation speeds are not uniform, but sinusoidal. The instantaneous maximum flow of inhalation is 3.14 times of the average respiratory volume, and the airflow speed is also one of the key factors affecting the mask. The increase in airflow (breathing volume) resulted in the decreases of mask FE.

4. Limitations

There are some limitations for this study. First, it is worth noting that the FE data were obtained from a limited number of experiments by using SBF to generate aerosols under specific indoor conditions. Since the composition and state of respiratory droplets/aerosols largely depend on the large inter-person variability in human exhalation events, such as talking and coughing, and environmental factors, such as humidity, temperature, air exchange rate, and airflow, SBF aerosols in the present experiment were quite different from real viral aerosols (Gregson et al., 2020). It should be noted that FE for mask wear time only was done by recruiting volunteers, while FE for other factors such as temperature and humidity, aerosol size and expiratory volume were under simulated conditions. Second, this experiment did not consider the impact of the particles falling off the mask itself that may affect the results. Compared with N95 and surgical masks, more particles fall off from homemade masks when rubbing a mask with hands (Asadi et al., 2020). The particulate matter blown by the mask itself due to the airflow could cause deviations in the results and render the tested FE numerically low. Third, we did not consider the leakage through the gaps around masks due to improper mask wearing or mask design. Surgical masks and cloth masks are not designed to fit, and in normal usage would result in unfiltered air being inhaled and exhaled through the gaps. A large number of studies have reported that the gap between the individual facial contour and mask caused by improper fit could significantly affect the FEs of masks (Grinshpun et al., 2009; Steinle et al., 2018). Small gaps between the mask material and skin can lead to substantial decreases in the overall FE. As an example, for aerosols < 2.5 μm, FE could decrease by 50% for a relative leak area of 1% (Drewnick et al., 2021). When people wearing face masks in everyday life, the leakage of mask and face contour could significantly reduce the FEs, therefore increase the infection risks (Lawrence et al., 2006; Lee et al., 2008). This is an important caveat in comparing N95 with surgical masks.

The use of a fit brace, however, can improve the seal around a cloth or disposable mask. Double masking has recently been recommended in the US (CDC, 2021), and it was estimated that the better fit achieved by combining these two mask types, specifically a cloth mask over a medical procedure mask, could reduce a wearer's exposure by >90% (Brooks et al., 2021), according to the FE experiments of various cloth masks and medical procedure masks.

5. Implications

Masks are used globally for preventing the spread of aerosol particles and protecting people from infection, with mask mandates in many countries during the pandemic. We have shown that the quality of filtration of different masks varies by mask, and by aerosol particles at different size. To the best of our knowledge, this is not the "first experiment" to explore the FEs of different mask types (Whiley et al., 2020; Leung et al., 2020; Pan et al., 2021; Sterr et al., 2021; Ueki et al., 2020). But this study shows that FE decreases significantly as the wearing time or respiratory volume increases. We assessed the FE of 4 types of commonly used masks in the context of different breathing volume and different particle sizes. In addition, the influence of different wearing time on the FE of masks was also determined, which can guide the public to use masks correctly. Our findings can be used to inform policies regarding the use of masks for general public in current and future pandemics. Wearing masks alone may still not enough to efficiently prevent the spread of coronavirus. For general public, people still need to take other countermeasures to protect themselves, for example, washing hands regularly, maintaining a social distance, using proper cough etiquette, and ensuring good indoor ventilation. Masks will likely be required in the immediate future, during the roll-out of vaccination programs around the world, especially given vaccine supply shortages, slow uptake and varying efficacy of available vaccines.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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